Executive Summary

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ABSTRACT

The influence of greenhouse gases and particles on our present and future climate has been widely examined and most recently reported in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report. While both long-lived[9] (*e.g.* carbon dioxide) and short-lived[10] (*e.g.* soot) species affect the climate, previous projections of future climate, such as the IPCC reports, have focused largely on the long-lived gases. This Climate Change Science Program Synthesis and Assessment Product provides a different emphasis.

We first examine the effect of long-lived greenhouse gases on the global climate based on updated emission scenarios produced by another CCSP Synthesis and Assessment Product (2.1a). Unlike those used in the latest IPCC report, these scenarios were

[9] Atmospheric lifetimes for the long-lived radiative species of interest range from 10 years for methane to more than 100 years for nitrous oxide. While carbon dioxide's lifetime is more complex, we can think of it as being more than 100 years in the climate system. As a result of their long atmospheric lifetime, they are well-mixed and evenly distributed throughout. Global atmospheric lifetime is the mass of a species in the atmosphere divided by the mass that is removed from the atmosphere each year.

[10] Atmospheric lifetimes for the short-lived radiative species of interest range in the lower atmosphere from a day for nitrogen oxides, from a day to a week for most particles, and from a week to a month for ozone. As a result of their short lifetime their concentrations are highly variable and concentrated in the lowest part of the atmosphere, primarily near their sources.

constrained so that the atmospheric concentrations of the long-lived greenhouse gases leveled off, or stabilized, at pre-determined levels by the end of the 21st century. However the projected future temperature changes, based on these stabilization emission scenarios, fall within the same range as those projected for the latest IPCC report. Therefore we are able to use the very extensive analysis in the 4th Assessment Report of the IPCC to summarize the key global and regional climate projections for the stabilization emission scenarios produced by 2.1a. We confirm the robust future warming signature and other associated changes in the climate.

We next explicitly assess the effects of short-lived gases and particulates. Their influence is found to be global in nature, substantial when compared with long-lived greenhouse gases and potentially extending to the end of this century. They can significantly change the regional surface temperature (for example over the summertime continental US). It is noteworthy that the location of the simulated climate response is not local to the forcing. This has implications for regional air quality control strategies and also reveals the necessity for explicit and consistent inclusion of these pollutants in further assessments of future climate.

1. Key Results and Findings

These results constitute important improvements in our understanding of the influence of both long-lived gases and short-lived gases and particulates. The Fourth Assessment Report of the IPCC recognized that most of the global-scale warming since the middle of last century was very likely due to the increase in greenhouse gas concentrations, and also that the warming has been partially damped by increasing levels of short-lived particles. However, while the IPCC models were coordinated in using identical greenhouse gas emission scenarios, the short-lived radiatively active pollutants were widely varying in the emission scenarios used, and their future impacts were not isolated from the long-lived gases

This Synthesis and Assessment Product is able to provide a more comprehensive and updated assessment of the relative future contributions of long and short-lived gases and particulates, with special, explicit focus on the short-lived component. This study encompasses a realistic time frame over which available technological solutions can be employed, and this study in particular, focuses on those gas and aerosol species whose future atmospheric levels are also subject to reduction due to air pollution control.

1. Climate projections from CCSP 2.1a stabilization emission scenarios[11] generally fall within the IPCC range of projections for their standard storyline scenarios. The most extreme stabilization scenarios, which are equivalent to a carbon

[11] Stabilization scenarios are a representation of the future emissions of a substance based on a coherent and internally consistent set of assumptions about the driving forces (such as population, socio-economic development, technological change) and their key relationships. These emissions are constrained so that the resulting atmospheric concentrations of the substance level-off at a pre-determined value in the future.

dioxide stabilization level of 450 ppm, result in global surface temperatures below those calculated for the most moderate IPCC scenario, particularly beyond 2050. Nonetheless, all of them unequivocally cause warming across the range of possible emission scenarios.

2. By 2050, changes in short-lived pollutant concentrations in two of the three studies contribute 20-25% of their simulated global-mean annual average warming. Further, our results suggest that the short-lived species significantly influence climate out to 2100. The presence of radiatively active[12] short-lived species can significantly change the regional surface temperature response (for example over the summertime continental US).
3. The range of plausible short-lived emissions projections is very large, even for a single well-defined global socio-economic development scenario. This currently limits our ability to provide definitive statements on their contribution to future climate change. The three comprehensive climate models[13] and their associated chemical composition models[14] participating in this report produced differing outcomes. Each model represents a thoughtful, but incomplete characterization of the driving forces and processes that are believed to be important to the climate or to the global distributions of the short-lived species. Much work remains to be done.

[12] Radiatively active indicates the ability of a substance to absorb and re-emit radiation, thus changing the temperature of the lower atmosphere.
[13] A comprehensive climate model is a state-of-the-art numerical representation of the climate based on the physical, chemical and biological properties of its components, their interactions and feedback processes that accounts for many of climate's known properties. Coupled atmosphere/ocean/sea-ice General Circulation Models (AOGCMs) provide a comprehensive representation of the physical climate system.
[14] Chemical composition models are state-of-the-art numerical models that use the emission of gases and particles as inputs and simulate their chemical interactions, global transport by the winds, and removal by rain, snow and deposition to the earth's surface. The resulting outputs are global three-dimensional distributions of the initial gases and particles and their products.

4. We find that the geographic (spatial) distribution of forcing is less important than the spatial distribution of climate response. Thus, both short-lived and long-lived species appear to cause enhanced climate responses in the same regions rather than short-lived species having an enhanced effect primarily in or near polluted areas. This means that regional emission control strategies for short-lived pollutants will have large-scale climate impacts.
5. The two most important uncertainties in characterizing the potential climate impact of short-lived species are found to be the projection of their future emissions and the determination of the indirect effect[15] of particles on climate. The fundamental difference between uncertainties in future emissions and uncertainties in processes, such as the indirect effect of particles, is discussed in section 4.3.
6. Natural particles such as dust and sea salt also play an important role and their emissions and interactions differed significantly among the models, with consequences to the role of short-lived pollutants. This inconsistency among models should be reconciled in future studies.
7. Emissions reductions of soot in the domestic energy/power sector in Asia appear to offer the greatest potential for substantial, simultaneous improvement in local air quality and reduction of global climate change.

[15] The indirect effects of particles lead to an indirect forcing of the climate system through their acting as cloud condensation nuclei or modifying the optical properties and lifetime of clouds.

2. Recommendations for Future Research

The four most critical areas for future research identified in this Report are:

1. The projection of future human-caused emissions for the short-lived species;
2. The of indirect and direct effects of particulates and mixing between particulate types;
3. Transport, deposition, and chemistry of the short lived species.
4. Regional climate forcing vs. regional climate response.

1. Plausible emission scenarios for the second half of the 21st century show significant climate impacts, yet the range of plausible scenarios is currently large and some increase in confidence in these scenarios is necessary. Short-lived species, unlike the well mixed greenhouse gases, do not accumulate in the atmosphere. Therefore, combined with a large range of possible emission scenarios, the climate impact of the short-lived species is currently extremely difficult to predict. Improvements in our ability to predict social, economic and technological developments affecting future emissions are needed. However, uncertainties in future emissions will always be with us. What we can do is develop a set of internally consistent emission scenarios that include all of the important radiative species and bracket the full range of possible future outcomes.

2. The aerosol indirect effect, which is very poorly known, is probably the process in most critical need of research. The modeling community as a whole cannot yet produce a credible characterization of the climate response to aerosol/cloud interactions. All models

(including those participating in this study) are currently either ignoring it, or strongly constraining the model response.

3. The three global composition models in this study all employed different treatments of mixing in the lowest layers of the atmosphere, transport and mixing by turbulence and clouds, removal of gases and particles by rain, snow and contact with the earth's surface, and different approximate treatments of the very large collection of chemical reaction that we do not yet fully understand. Further research is needed in all of these processes.

4. The major unfinished analysis question in this study is the relative contribution of a model's regional climate response, as opposed to the contribution from the regional pattern of radiative forcing[16], to the observed regional change in seasonal surface temperature. Is there a model independent regional climate response? What are the actual physical mechanisms driving the region temperature patterns that we observe? This appears to be a very important area of study, particularly given the apparently strong climate response in the summertime central US.

3. Guide to Readers

For those readers who would like to learn more about the research behind the Key Results and Findings and the Recommendations for Future Research, we provide the

[16] Radiative forcing is a measure of how the energy balance of the Earth-atmosphere system is influenced when factors that affect climate, such as atmospheric composition or surface reflectivity, are altered. When radiative forcing is positive, the energy of the Earth-atmosphere system will ultimately increase, leading to a warming of the system. In contrast, for a negative radiative forcing, the energy will ultimately decrease, leading to a cooling of the system. For technical details see Box 3.2

following guide to reading the four chapters. Chapter 1 provides an introduction to this study and relevant findings from previous climate research, introduces the goals and methodology, and provides Box 1.1 and Box 1.2 with relatively non-technical descriptions of the modeling tools and definitions of terms. It is written in a non-technical manner and is intended to provide all audiences with a general overview. Chapters 2 and 3 provide detailed technical information about specific models, model runs and trends and are intended primarily for the scientific community, though the key findings and the introduction to each chapter are written in non-technical language and intended for all audiences. Chapter 4 is intended for all audiences. It provides a summary of the major findings and identifies new opportunities for future research.